APPENDIX B
Low—Cost Space Transportation

THE DIMENSIONS OF LOW—COST SPACE TRANSPORTATION

As the Apollo program comes to a close and with it the end of man's first decade in space, many thoughtful people are asking "What next?" Two extremes of thought delimit the answer to this question.

On the one hand, our remarkable progress has erased almost all doubt about man's ability to travel in space and has led many to believe that space offers a worthy challenge for the human spirit. To these people it is only a matter of time until we make the planetary system inhabitable and interconnect it with a vast space transportation network. At the other extreme are those who oppose the large expenditures of the space program and urge that it be terminated and its budget be used in solving some of our more immediate and pressing problems. A sober appraisal shows that the dreams of the space enthusiasts may never materialize if the taxpayers become disenchanted and are no longer willing to pay the costs.

A major factor in the debate has been the high costs of the space program. With each space flight costing tens or hundreds of millions of dollars it is difficult to argue that space travel can ever become commonplace. Why is the space program so expensive and what are the prospects of reducing space costs to reasonable levels?

To place various costs in perspective, table B-I has been constructed. The scale on the left is logarithmic and shows dollars ranging over 12 powers of 10.

In the first column a few pertinent annual rates have been listed. The U.S. gross national product stands at about 12 powers of 10,

Table *B-I –Various Cost Comparisons in Relation to NASA Costs*

Cost in dollars	Annual rates	Development costs	Per vehicle	Per flight	Per ticket
10^{12}	USGNP				
	Federal budget				
10^{11}					
10^{10}	NASA	Saturn V			
		SST		Saturn V	
10^{9}			Saturn V		
10^{8}		707		Saturn IB, Titan III	Saturn V
			SST		
10^{7}			707		
10^{6}					
		Early airplanes			
10^{5}	↑				
	Individual salaries				
10^{4}			Autos	SST, 707	
	↓				↑ Airline
10^{3}					
10^{2}				↑	↓ Bus
				Auto	
10^{1}					
				↓	↑
10^{0}					↓

the Federal budget at about 11, and NASA's annual expenditure at about 9-1/2. Considerably lower, we see salaries of individual citizens ranging from 3 to 5 powers of 10.

In the second column we have listed the cost of developing various systems that are of interest here. The total development cost for the Saturn V system is about 9-1/2 powers of 10. The projected cost of developing the supersonic transport is about 9, and the development of the 707 jet airplane cost about 8. The cost of developing early airplanes must have been about 5.

When we ask about purchasing individual vehicles, we see that a Saturn V costs about 8 powers of 10, an SST about 7-1/2, and a 707 under 7. Automobiles are about 3-1/2.

The cost of a single flight of Saturn V is about twice that of the vehicle alone, that is, between 8 and 9. Saturn IB and Titan III are a little less—between 7 and 8. And now we come to the significant fact that the cost per flight of a 707 is just over 3 powers of 10 and the cost of an SST flight is not going to be much more. The cost of the average auto trip ranges from 0 (i.e., $1) to 1-1/2 powers of 10.

Finally we examine the price of purchasing a ticket. If you were to go to NASA and ask to buy a ticket on Saturn V, NASA would have to charge you between 10^7 and 10^8 dollars. On the other hand, if you go to an airline it is difficult to pay more than 3 powers of 10—or to pay less than 1. Bus fares are somewhat less.

Now that we have completed the table, let us stand back and take an overall look. The most penetrating fact is that there are about 4 to 6 powers of 10 difference between the cost of a ticket on Saturn V and that on a commercial airliner.

The Saturn V ticket price is appropriate for NASA because it represents a reasonable fraction of NASA's budget. And the airline ticket is reasonable for the average citizen to pay because it is an appropriate fraction of his annual salary. Similarly, the price of a Saturn V and that of an automobile are each reasonable for the person buying them. But if space travel is to become commonplace for the average citizen, it is abundantly clear that ticket prices cannot be based on NASA's budget.

Hereafter, when we speak of low-cost space transportation, we define low to be so low that the average citizen can afford to buy tickets for space. Short of this, space transportation can never become commonplace.

Is it a dream to talk of reducing space costs by 4 to 6 powers of 10?

First, let us see why costs are high. Here one finds the technical and public literature filled with myths. A typical myth says that money for space has been easy to come by, and as a result funds have been squandered to a point where costs have become exorbitant. A different version of this myth claims that costs are high because we have overemphasized safety and because the testing program has pushed costs out of sight. Common sense says that waste and/or caution may account for modest increases, but not 4 to 6 powers of 10.

The table bears this out. The supersonic transport is not too different in size, weight, and complexity from Saturn V, and its development cost is within a half a power of 10 of being the same. And even with its billion-dollar development cost, it is expected to be a commercial success, with tickets selling in direct competition with subsonic aircraft. If space and airline tickets were in direct proportion to their development costs, space transportation would be low-cost transportation. Clearly, development costs are not the cause for which we are searching.

Another myth states that space travel is inordinately expensive because rocket engines have enormous appetites. This myth clinches the point by saying that if commercial airliners had to use rocket engines for propulsion, they would be economic failures. Let us take a closer look.

A space vehicle and a jet transport, each in its own environment, are comparably efficient. The rocket starts off with an enormous gulp of propellant, but afterwards it goes on and on, and on—free. The jet airplane uses fuel at a much more modest initial rate, but must use and use and use throughout its entire flight. The propellant and fuel costs of Saturn V and the supersonic transport are less than 1 power of 10 apart; sufficiently close, in fact, to show that these costs cannot explain 4 to 6 powers of 10.

Another version of this myth claims that space transportation is inherently expensive because the distances involved are so great. This argument goes on to say that in fairness to space transportation, costs should be reckoned on a dollars-per-mile basis. Such an argument, if correct, would refute the belief that space transportation can ever become commonplace. However, the numbers themselves do not stand up. At 10 cents per mile, a round-trip ticket to the Moon should cost $40 000, which is several powers of

10 short of the actual cost, and more than the average citizen can afford.

We could go on examining purported causes for the high cost of space transportation, but it is more profitable to ask–what is the real reason. This is not hard to find.

If a supersonic transport lasted for only one flight and carried only a handful of passengers, a ticket would cost within 1 power of 10 of that for Saturn V. This leads inescapably to the conclusion that we must get vastly increased utilization in proportion to the expensive investment required for a space vehicle. To do this we must:

(1) Reuse the same vehicle over and over (several powers of 10).

(2) Reduce the cost of each reuse (including refurbishment and relaunching) so that it is small when compared to the cost of building a new vehicle (by several powers of 10).

(3) Increase the utility or productivity of the space vehicle. In the case of probes, laboratories, and observatories, this means obtaining a vast amount of scientific or technical information during the lifetime of the spacecraft. In the case of space stations, factories, and the like, it means processing or producing sufficiently large amounts of data or materials to pay for the large initial cost. In the case of space transportation, it means carrying a large amount of revenue-paying cargo and passengers. Item 3 does not concern us, because engineers have a natural aptitude for moving in this direction. It is items 1 and 2 that require attention.

WHY NOT REUSABILITY? THE FACTS OF LIFE ABOUT ROCKET VEHICLES

In view of the preceding discussion, one would think that there should be a great hue and cry against throwing away space vehicles after only one use. But there are perfectly good reasons why this is not so. Let us look at the basic facts about the design of rocket vehicles.

As a rocket vehicle sits on the pad, ready for launch, its gross weight W can be divided into three significant parts. The first is payload P, which consists of everything that the "customer" would be willing to pay revenue to take along. The second is weight F of the propellants used during the flight. The third is all the remaining weight, which we shall call "structure" and designate by S. This last

item includes tanks, rocket engines, electronic components, guidance, etc.

The fundamental equation for rocket vehicle performance is

$$V = -C \log_e \left(\frac{S}{W} + \frac{P}{W} \right)$$

where V is the integrated velocity achieved by the vehicle (including the effective velocity needed to overcome gravity and air resistance) and C is the exhaust velocity of the rocket (which is the specific impulse multiplied by the acceleration of gravity).

Now let us look at the significance of the various terms in this equation. Velocity V depends on the mission. About 26 000 ft/sec are required to go into orbit and about 36 000 ft/sec to break away entirely from the Earth's field. With regard to exhaust velocities C, early rockets achieved velocities of 8000 ft/sec and modern rockets have pushed this up to about 14 000 ft/sec. Concerning weights, one finds that for a given vehicle it is possible to exchange payload for propellants on a nearly even basis, without altering the gross weight. One also finds that the ratio of the structural weight to the gross weight depends almost entirely upon the state of technological development, and very little upon the size of the spacecraft. In early space vehicles, the ratio for S/W was about 0.24; in current technology, S/W is more nearly 0.06. The net effect of the above statements is that the designer first obtains the best ratio of S/W that he can. He next determines the propellant ratio F/W to suit his mission requirements (if he can), and then scales the entire spacecraft up or down to meet the size of payload desired.

To see how all this works, we have plotted in figure B-1 the ratio of vehicle velocity to exhaust velocity versus the ratio of gross weight to payload for various ratios of structural weights to gross weight. Let us first examine the problem faced by an early designer in trying to place a vehicle in orbit and having at his disposal an exhaust velocity of the order of 8000 ft/sec and a structural weight ratio of 0.24. Because orbital velocity is approximately 18 000 ft/sec, he needs a V/C of 2.3. Having picked a payload weight, he enters the chart along the line S/W=0.24, hoping to run up the gross weight to a point where he can achieve V/C=2.3. Following out along the S/W=0.24 curve to larger and larger values of gross weight, he quickly finds that the curve reaches an asymptotic value of V/C=1.43, and that even an infinite-size vehicle would not permit him to achieve an orbital value of V/C=2.3. Stopped on this front,

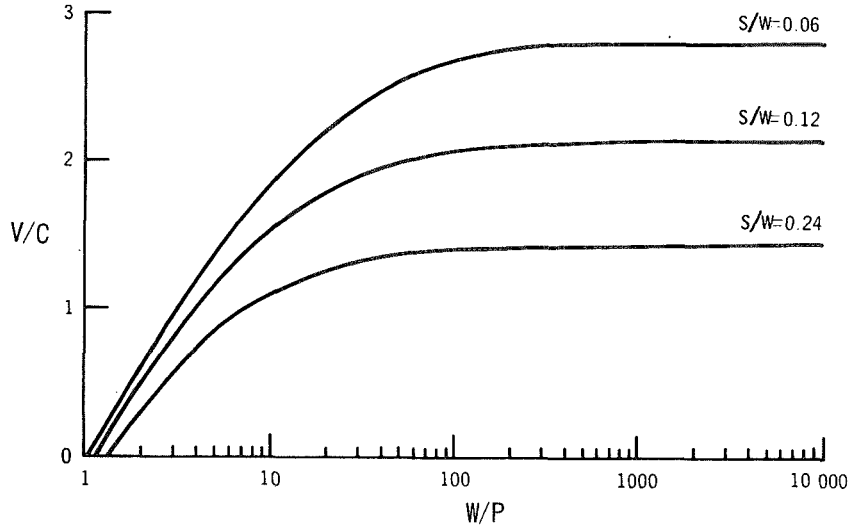

Figure B-1.–Ratio of vehicle velocity to exhaust velocity versus ratio of gross weight to payload for various ratios of structural weights to gross weight–single-stage.

he exercises his ingenuity in the following way. Using a modest size vehicle to carry his primary payload, he carries this vehicle along as the "payload" of a larger vehicle which, if necessary, can be carried along as the payload of a still larger vehicle, and so on. This use of multiple stages has the following powerful advantage. As the rocket uses up its propellants it lightens its load and thus obtains the greatest increase in velocity during the final moments of burning. This last burst of speed is limited by the onboard weight which, for a hard-pressed vehicle, is largely structural weight. With tanks nearly empty, much of this structural weight is no longer needed, and if it could be discarded, the final burst of speed could be greatly increased. Staging is the designer's way of progressively discarding no longer needed weight to achieve just such an advantage.

With optimum proportioning of stages, the performance equation, with n as the number of stages, becomes for a vehicle of n stages

$$V = -C \log_e \left[\frac{S}{W} + \left(\frac{P}{W} \right)^{1/n} \right]^n$$

When this is plotted, as we have done in figure B-2, the advantages

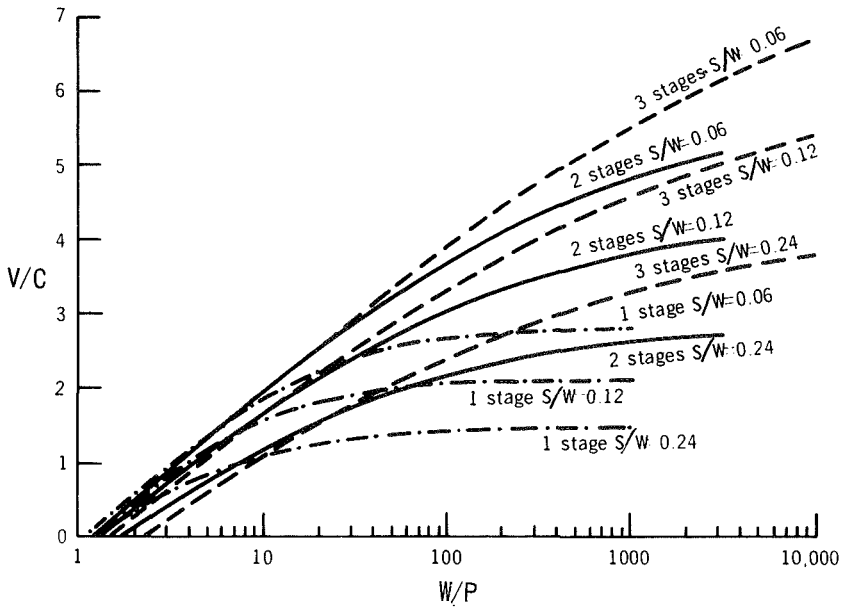

Figure B-2.—Ratio of vehicle velocity to exhaust velocity versus ratio of gross weight to payload for various ratios of structural weights to gross weight—multiple-stage.

of using multiple stages is at once apparent. Now the designer is readily able to achieve his goal of V/C=2.3 for orbit. Furthermore, as he contemplates going to the planets and returning, he is no longer confronted by an asymptotic ceiling on the V/C's he can achieve. If he is willing to use successively larger vehicles and a successively greater number of stages, he can increase his mission capabilities virtually without limit.

With these thoughts about the great advantages of using multiple stages fresh in our minds, let us return to the question of costs. We immediately see why space vehicles are thrown away after only one use. During launch, each stage is used and discarded, with the largest and most expensive being discarded first. Everyone is so glad to get rid of the expended weight that few mourn the tens or hundreds of millions of dollars of equipment that falls into the sea. And it is easy to argue, convincingly, that recovery and reuse of our present systems could never be done for a cost substantially less

than the cost of building new vehicles. Accordingly, it is quite understandable that space engineers generally do not think in terms of the reusability operations that characterize other forms of transportation.

If one reads the early history of aeronautics, one finds that as long as aircraft speeds were comparable with the speed of the wind, fear of the wind loomed large in aeronautical thought. In a similar way, as long as it is a major effort to get into orbit, the problem of staging will loom large in the thought of space engineers. But once we can readily achieve orbit with a single stage, space economics will take on a whole new dimension. Space vehicles will be able to shuttle from the Earth's surface (or other planetary surfaces as well) into orbit and back with operations similar to those of the airlines. Furthermore, staging for interplanetary travel will no longer require the discarding of used vehicles. Once a vehicle can go directly into orbit, it can deposit its cargo in a space depot and return for another load. And an interplanetary vehicle can go into orbit, refuel at the space depot, voyage out into space, orbit around one of the other planets, and descend–all as a single-stage vehicle. When this becomes possible, people will begin to ask innocently what the problem of economical reuse was all about.

How close are we now to being able to achieve orbit with a single stage? Rocket exhaust velocities have risen to 14 000 ft/sec. For orbital velocities of 26 000 ft/sec, this gives a V/C of 1.8. Structural weight ratios have decreased to about 0.06. Entering figure B-1 with these numbers, we see that we are now able to launch single-stage vehicles directly into orbit. This ability has come only with the last generation of space vehicles. The door is thus open for the next generation to usher in low-cost space transportation.

In closing this section, let us put the larger problem in perspective. If we are to have an economical, reusable space transportation system, we must abandon such archaic techniques as parachute landings and recovery by task force. There will be penalties in structural weight for vehicles which will be part of a smoothly flowing transportation system, but technological progress will certainly make this possible.

NASA'S ROLE IN LOW-COST SPACE TRANSPORTATION

We are at the end of one era and the beginning of another. We will soon complete President Kennedy's goal of going to the Moon, and must now plan for the next decade. Thus far, the slate is virtually blank.

Let us look at the avenues open to NASA. We begin by focusing attention on two important variables. The first is the total amount of money that NASA may have to spend during the 1970's, and the second is the approximate level of flight activities that NASA will elect to pursue. This latter variable is measured in terms of pounds of payload launched into space. Our discussion will center around figures B-3 and B-4, where these two variables appear as ordinate and abscissa.

From figure B-3, we can immediately indicate some of the constraints upon the space program. Federal expenditures for the 1970's will total about $\$2 \times 10^{12}$. It is inconceivable that NASA's budget could exceed about 10 percent of this figure. This gives a ceiling of about $\$2 \times 10^{11}$ for NASA's expenditures. Furthermore, if one examines the basic necessities for conducting space operations (tracking network, launch facilities, etc.), one finds that over a 10-year period this gives a floor of about $\$10^{10}$, which is about one-fourth of NASA's present rate. Concerning flight activity, a typical flight now places about 10^5 pounds of payload in space. If NASA launched less than one flight per year, the whole program would cease to be viable, because operational teams could not maintain their proficiency and the taxpayers would feel the results were not worth the cost. This gives a lower limit of 10^6 pounds of payload to be launched into space during the decade.

Because we are plotting cost versus payload into space, we can place on our chart (fig. B-3) a scale of cost per pound of payload. This has been done by means of the diagonal lines. Referring to our earlier discussion where "low-cost space transportation" was defined to be that which brings the price of a ticket within the reach of the average citizen (and accepting the fact that the average citizen, with baggage, weighs 200 pounds and can afford to pay $500 to $5000 for a space ticket), we can label that portion of our scale lying between $2.50/lb and $25/lb as "low-cost transportation."

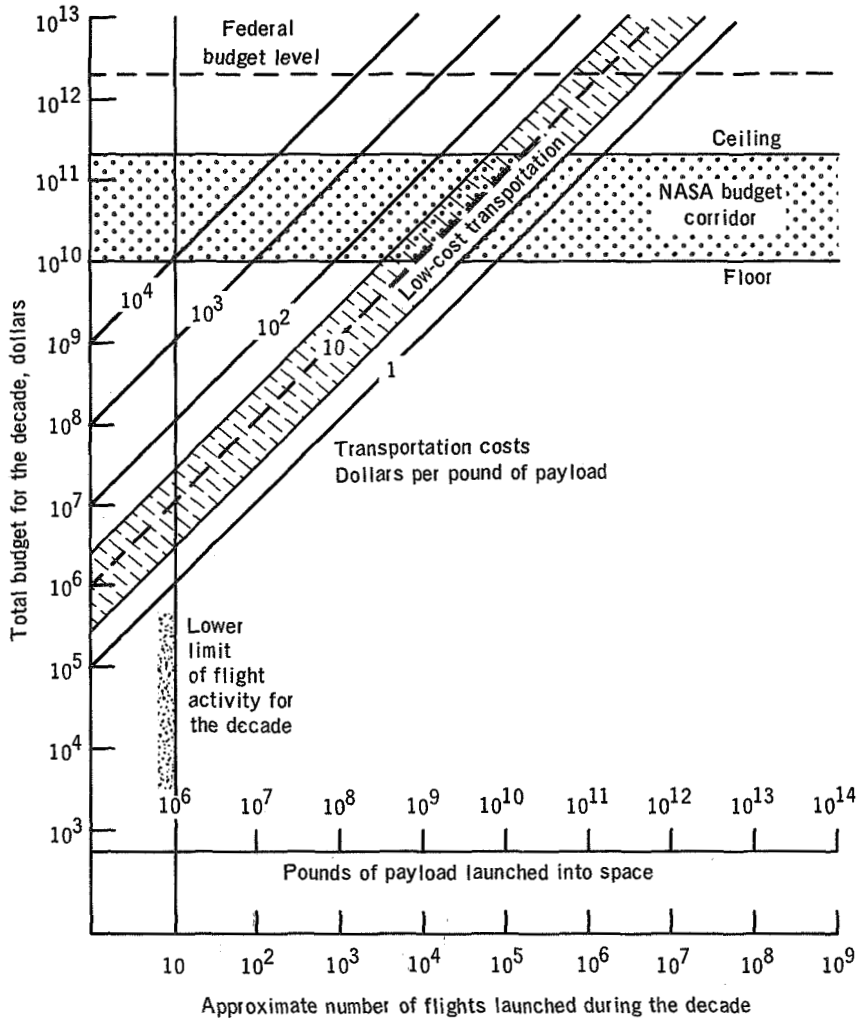
Federal budget level
Ceiling
NASA budget corridor
Floor
Low-cost transportation
Transportation costs
Dollars per pound of payload
Lower limit of flight activity for the decade
Total budget for the decade, dollars
Pounds of payload launched into space
Approximate number of flights launched during the decade

Figure B-3.–Space budgets and flight activities during the decade of the 1970's–NASA costs in relation to low-cost transportations.

Across the bottom of the chart, we can place an approximate scale showing the number of space flights undertaken during the 10-year period, if we assume typical payloads of 100 000 pounds per flight. This figure may be in error by a factor as great as 5, but it will serve to give an indication of flight activity to be expected during the decade.

Even with no further data on the chart, we can immediately see the potential impact of low-cost transportation on NASA operations. If low-cost transportation were a reality, NASA could plan to undertake somewhere between 4000 and 40 000 flights before flight costs would begin to absorb a major share of their base budget. At these levels, the nation would surely feel that it was getting its money's worth.

Let us now examine what it takes to go from where we are now to the situation in which low-cost space travel would be a reality.

The cost of a Saturn V flight is about $\$2\times 10^8$. If we assume that the "learning curve" or the "law of economic improvement with increasing scale" permits flight costs to drop by 20 percent each time the number of flights is doubled, then accumulated flight costs will not rise in direct proportion to the number of flights, but instead will go up approximately as the two-third power of the number of flights. On figure B-4 we have drawn a line showing projected Saturn V costs. To use only Saturn V throughout the 1970's is not very imaginative, but the curve we have drawn shows, surprisingly, that NASA could launch approximately 40 million pounds of payload into space before flight costs would begin to absorb a major share of their base budget. At this level, the cost of each flight would have dropped by a factor of 7. To see more explicitly how such activity might affect NASA's budget, let us assume that the Saturn V costs are added to the base budget of $\$10^{10}$ needed to keep NASA in existence. We then obtain curve A on figure B-4. From this we can draw the conclusion that using Saturn V alone will not permit NASA to get into the realm of low-cost transportation, because the ceiling we have placed upon NASA would be exceeded before such a goal would be reached. However, without undue strains upon even the minimal budget, NASA could readily launch many more flights than are now under discussion. If there is a lesson to be gained from this, it is probably that serious pressure upon NASA to increase its flight activity could produce dramatic results.

Turning to the question of reducing costs below those of Saturn V, two different options would appear to be open. One would be to retain our present techniques but to make straightforward improvements that would reduce costs by factors of perhaps 2 or 4. The other would be to make a major change, designing single-stage-into-orbit vehicles capable of cheap multiple reuse. Here the goal would be to reduce costs by factors of 10 or 100. As we saw in the

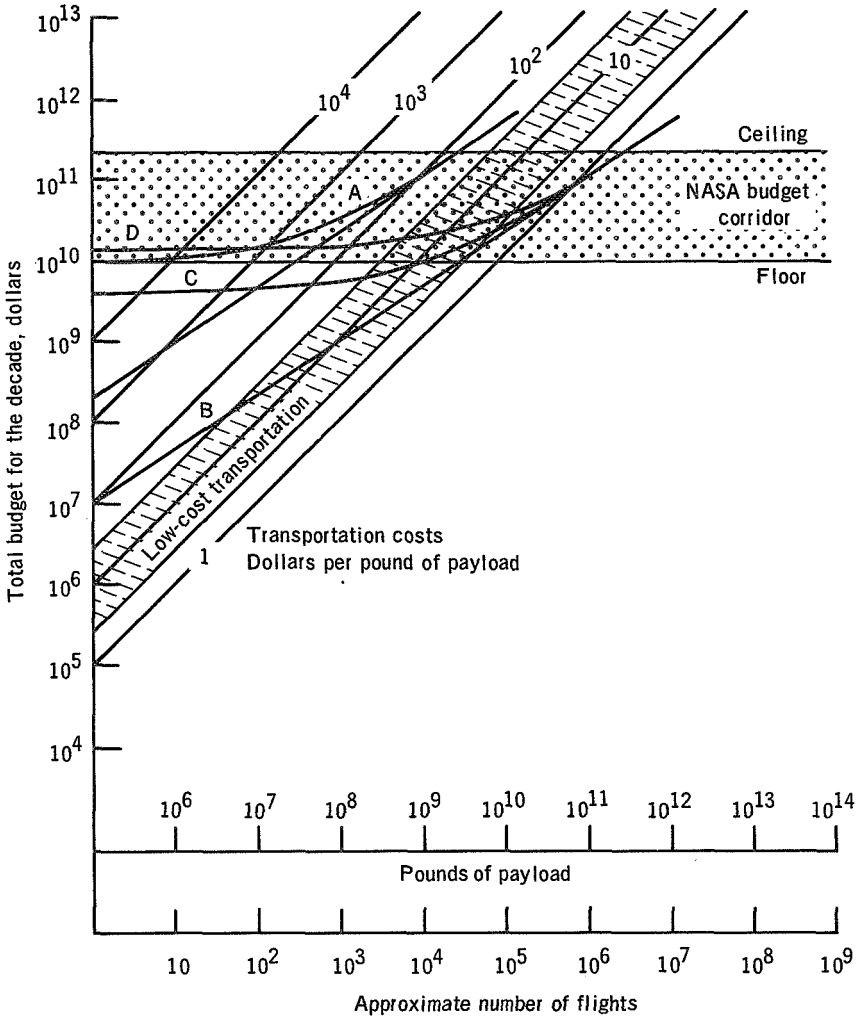

Figure B-4.–Space budgets and flight activities during the decade of the 1970's–Saturn V costs in relation to single-stage development option costs.

preceding section, our technology has now advanced to a point where this latter option would appear to be an attainable goal for the next generation of space vehicles.

Let us examine this latter option more carefully. First, let us

assume that it would permit us to reduce flight costs to one-twentieth of those of Saturn V. On figure B-4, this has been shown by curve B. Because it is likely that the development costs for such a system would be as great as those for Saturn V, curve C reflects the costs when we add this development cost to the flight costs of curve B. Finally, if we add the costs of curve C to the base budget necessary to keep NASA in existence, we obtain curve D.

Let us now compare the costs of such a system with those of Saturn V as given by curve A. We see at once that if NASA were to pursue a policy of limited flight activity (less than 100 flights during the decade), then the Saturn V system is cheaper. On the other hand, if NASA launches many flights, the revised system is cheaper. Furthermore, the revised system would permit NASA to launch literally thousands of flights before flight costs would make a substantial increase in the total budget. What is most significant is that such a system would readily enable NASA to get into the "low-cost transportation" belt.

I can give no guarantee of NASA's ability to produce a system that would yield costs of the order of magnitude represented by curve D. To me, the evidence is convincing that curve D is a feasible goal. If it can be achieved, the results would open whole new vistas for the future of the space program.